An analysis of the potential of envelope-integrated solar heating and cooling technologies for reducing energy consumption in European climates

Peru Elguezabal, Beñat Arregi

TECNALIA Sustainable Construction Division, Parque Tecnológico de Bizkaia, Derio Spain

Abstract

There is a clear trend towards the increased contribution of renewable energy at European level, and EU policies are oriented in this direction. The building sector is no exception and presents an urgent need for increasing the share of renewable energy sources (RES) to reduce the impact on the environment.

The aim of this paper is to examine the potential of solar heating and cooling technologies in reducing energy consumption by incorporating solar thermal and PV collectors within the building's envelope. Although generally envisaged as being integrated into the roof, preferably oriented to the south, this study explores their potential for integration into building façades.

External climate influences both the demand for space heating and cooling (influenced by temperature) and the potential of solar renewable energy (incident global irradiation). However, a time lag exists since supply and demand peak at different times within the day as well as during the year.

This study assesses the interplay of solar energy supply with heating and cooling energy demand. An analysis is performed over climate data files for five European locations, based on daily weather data. Besides the extent of incident solar irradiation, its seasonal usability is assessed with regard to the thermal demand. The impact of the inclination of solar collector devices is assessed by comparing their placement on a horizontal plane, on the inclination of maximum exposure for each climate, and on vertical planes for the four cardinal directions.

As a conclusion, the utilisation of solar energy in different scenarios is assessed and a discussion on the integration of solar thermal and PV collectors on façades is presented, building on the potential of these technologies for developing innovative solutions that could significantly upgrade the buildings' energy performance in the near future.

Keywords

façade integrated solar technologies, solar heating, solar cooling, solar collectors

DOI 10.7480/jfde.2018.2.2102

1 INTRODUCTION

The poor state of the building sector in relation to energy consumption, efficiency, and associated impacts such as CO_2 emissions is a well-known problem (UNEP - SBCI, 2009). The challenge posed by the EU's ambitious goals for 2020, 2030, and 2050 (European Commission, 2017) has stated a clear position looking to correct this course and achieve a significant improvement over the current situation. In such a scenario the necessity for a higher contribution to come from renewables is undisputable. This is clearly stated by the EU in the Nearly Zero Energy Building (NZEB) definition (European Commission, 2010), in which, in addition to the maximum admissible primary energy consumption in buildings, a minimum contribution from Renewable Energy Sources (RES) is demanded. The Directive also specifies that this energy must be produced "on-site or nearby". Due to the complex development of the NZEB concept within different member states with varied interpretations of that definition, the Commission has also published some recommendations (European Commission, 2016), to provide quantifiable references that could help to better explain what is expected. Specifically, it distinguishes four major climatic zones in Europe (Mediterranean, Oceanic, Continental, and Nordic) and sets the minimum renewable contribution in relation to each of these zones, within a range of 28-77% for new single-family houses and 30-70% for the case of office buildings. This represents an effective yearly coverage over the primary energy of 25-50 kWh/m^2 and 30-60 kWh/m^2 respectively. The path described for these cases should be the main goal to be achieved by all buildings in any future scenario, and places significant focus on renovation works. This is a critical point as, according to the International Energy Agency, approximately 60% of the current building stocks will still be in use in 2050 in the European Union, United States, and Russia (IEA, 2013).

Once the requirement to incorporate RES in buildings is accepted, there are various ways to execute these technologies in buildings, from independent devices attached to buildings to solutions that look for a higher integration, taking into consideration that this concept accepts different interpretations. Given the complexity of the processes of energy harvesting, storage, and distribution, the method for combining renewable systems and bringing them into buildings is a major challenge. At present, there is a set of systems and technologies that, taking benefit from the energy provided by the sun, can significantly contribute to the reduction of energy consumption in buildings. These systems, which are labelled as renewable, are already commercially available in some cases, while others are still in development. Solar thermal collectors, PV collectors, heat pumps over a certain performance, thermal storages, batteries, and management systems are the key components that have been identified as the means to achieve solar heating and solar cooling transformation. On the other hand, there seems to be no single measure that can solve the whole problem, but combinations and systems brought together can provide various solutions under holistic approaches.

Although existing technologies and solutions do have great potential under optimum conditions, when these are brought into buildings, the impact and effect of different configurations is not fully obvious. Solar collectors are very rarely, if ever, displayed in a fully horizontal position. Discarding sun-following panels and assuming a fixed position, collectors are commonly oriented to the south (as far as possible) and with a certain slope that seeks to maximise solar gains over the complete year, this angle being a function of the latitude and the sun declination (Stanciu & Stanciu, 2014).

In the search for better architectural integration, specific and unique design solutions for solar collector devices are devised to suit individual buildings, considering the aesthetic benefits of integrating flush mounted panels in the roof, in the façade, or in any other angled plane limited by the constraints of the construction and type of the building. The integration of collectors on building façades can be especially appealing when installing them as seamless solutions. In addition to this, their placement on vertical planes offers additional benefits in terms of a more stable energy production when oriented to south (Munari Probst & Roecker, 2012). This approach foregoes the orientation and/or tilt that receives the highest overall annual irradiation, getting less energy in absolute terms. Nevertheless, a more regular production is obtained throughout the whole year, allowing a better management and distribution of energy and, additionally, avoiding or minimising problems in summer conditions, such as overheating and stagnation for thermal collectors, and efficiency losses in PV panels. In summary, many different possibilities are feasible for the integration of solar panels within the building envelope, but at present there is no clear strategy or guidelines in the bibliography to help in the definition of such integrated solutions and their suitability to specific European climates.

The main aim of this study is to address the potential of solar systems incorporated into the building envelope (O'Hegarty, Kinnane, & McCormack, 2016) for space heating and cooling, taking into consideration different climates and orientations, under a general scope that seeks to balance solar production and demand. As a result of the assessment, some recommendations and criteria for designing solar façades are provided, and a number of currently available technological solutions for the integration of solar collection devices are presented.

2 METHODOLOGY

An analysis of climatic data for five European locations is performed to determine the theoretical potential of solar collection technologies. The selected approach is based on the correlation between solar potential, expressed as global irradiance, and thermal demand, expressed in Heating Degree Days (HDD) and Cooling Degree Days (CDD). Given the variety in performance for different solar collection technologies, and the greatly varying insulation levels for different EU regions and construction periods (Elguezabal et al., 2018), this method has been selected to represent the generic solar potential of each climate, without restricting it to specific technologies or building types.

The adopted methodology is explained through the following steps:

1. The starting point is the data obtained from a statistical weather database (Meteonorm 6.0) (Meteotest, n.d.), providing the external ambient temperature as well as the incident solar irradiation over a horizontal plane with hourly resolution during a representative year.
2. Taking external temperatures as a reference, the necessity for heating is assumed to be activated once the external temperature goes below 15 °C, and correspondingly, there is cooling requirement once ambient air exceeds 20 °C. These base temperatures have been selected to allow comparison among different cases; actual base temperatures are dependent upon the specific case considered, influenced by the type of construction, insulation properties, etc. (Schoenau & Kehrig, 1990). The temperature difference from these base values, integrated over a whole year, will give an indication of the demand for heating and cooling, expressed as (HDD) and (CDD).

$$\text{Heating Degree Days} = \text{HDD} = \sum_{i}^{365} \text{hdd}_i \,, \quad \text{hdd}_i = \begin{cases} \left(288 - \overline{T_{amb_i}}\right), & \overline{T_{amb_i}} < 288\ \text{K} \\ 0 \,, & \overline{T_{amb_i}} \geq 288\ \text{K} \end{cases} \qquad (1)$$

$$\text{Cooling Degree Days} = \text{CDD} = \sum_{i}^{365} \text{cdd}_i \,, \quad \text{cdd}_i = \begin{cases} \left(\overline{T_{amb_i}} - 293\right), & \overline{T_{amb_i}} > 293\ \text{K} \\ 0 \,, & \overline{T_{amb_i}} \leq 293\ \text{K} \end{cases} \qquad (2)$$

3 The next step is to determine the available irradiation to cover these needs. As the database only provides hourly values for global irradiation over horizontal surfaces, the anisotropic sky model (Perez, Stewart, Seals, & Guertin, 1998) has been used to estimate the incident radiation over surfaces at different orientations and tilts.

4 A daily resolution has been adopted to uncouple the calculation from the specific storage system chosen. This assumes a thermal storage than can make use of the solar energy received at any moment over a given day, but cannot store the excess energy for longer than that 24-hour period. Seasonal energy storage is therefore not considered.

5 The usable solar irradiation has been defined as the irradiation received when a heating or cooling demand exists. Taking into consideration the average daily external temperature and comparing it with the thresholds (base temperatures) stated above, the irradiation received for a given day is assigned for heating or cooling. In the same line, the irradiation is considered unusable if a daily demand does not exist.

6 Once the heating/cooling demand and the solar production are combined, the possibilities of the solar energy to respond to these demands can be appreciated for each location and orientation.

7 Following the above method, the theoretical potential of the solar energy has been determined for different orientations and inclinations. In practice, due to different constraints, the optimal surface may not be always available or provide the sufficient area, and the solar potential might be affected by local conditions such as exposure to wind or shadowing from neighbouring buildings or objects.

8 Finally, practical recommendations are provided in terms of possibilities and interest for integrating different systems in building envelopes.

3 ASSESSMENT OF POTENTIAL FOR DIFFERENT EUROPEAN CLIMATES

Five locations have been selected as representative situations for a variety of conditions within Europe. Large cities with some of the highest heating and cooling demands are studied, as well as some more balanced scenarios. The selected cities were Stockholm, Dublin, Budapest, Madrid, and Athens.

For these cities, Fig. 1 provides information represented at three different levels:

- In the upper row, total global irradiation, expressed monthly, for a set of different planes: horizontal plane (commonly used in irradiation atlases), tilt of maximum incidence depending on the location, and vertical south, west, north, and east planes.
- In the middle row, monthly accumulated heating and cooling demand, expressed in HDD and CDD.
- In the bottom row, the share of usable overall irradiation that is exploitable for heating and cooling purposes, depending on the adopted plane (horizontal, maximum irradiation, south or west, assuming that west and east are practically equivalent).

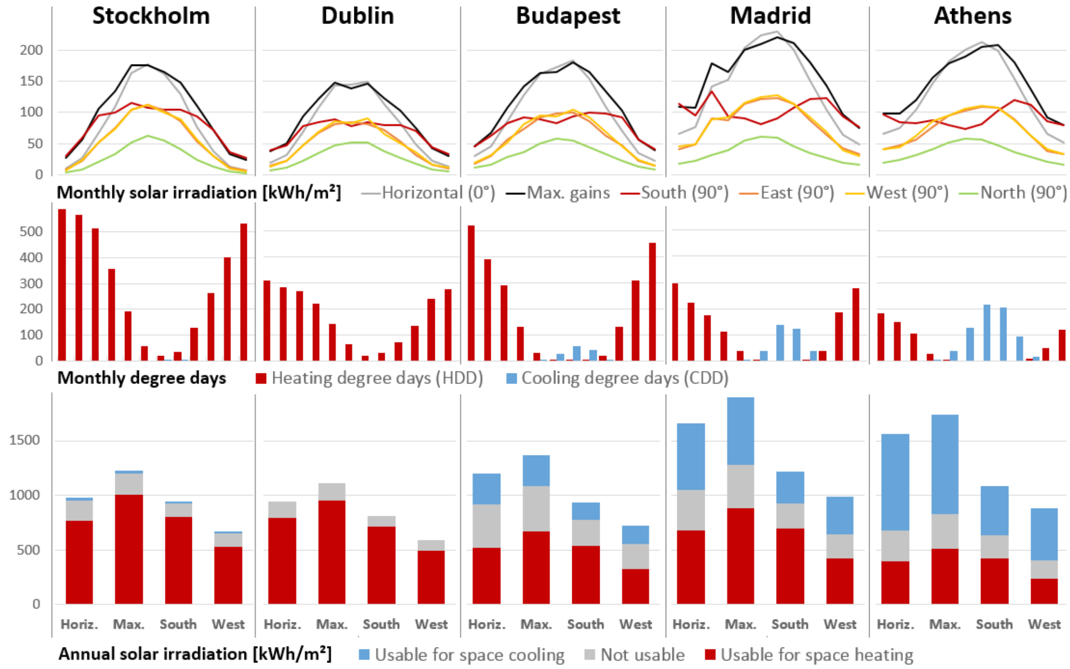

FIG. 11 Monthly global irradiation over different planes: horizontal, maximum incidence depending on the location, and vertical south, west, north, and east (top). Monthly accumulated heating and cooling demand (middle). Exploitable irradiation for heating and cooling purposes depending on plane (bottom).

4 RESULTS AND DISCUSSION

Besides the total available irradiation, it is crucial to consider what that energy is destined for, as well as the period when production and consumption are able to be combined. As expected, the predominance of the heating demand in most of the cases is clear, with more intensive demands at northern latitudes such as Stockholm, but also in severe continental climates, as for Budapest. Cooling demand is insignificant for Stockholm and Dublin, starts to appear at more southern latitudes with a very small requirement for Budapest, becomes higher in Madrid, and is the predominant demand in Athens.

The non-usable energy (grey in Fig. 1 bottom) relates to the solar irradiation received in those days where the space heating or cooling demand is null. For both Stockholm and Dublin, this portion is small, as some heating demand exists even during the months with maximum irradiance in summer (middle row in Fig. 1). In contrast, for the case of Budapest, the demand is quite low for those months, thus the solar energy is not conveniently exploited, making the non-usable proportion more significant. On the other hand, in Madrid and Athens, the energy harvested during the summer has a strong potential to be used for solar cooling.

When considering the usable solar energy in its maximum amplitude, Dublin presents an interesting result: while being the city with lowest irradiation (even below Stockholm which is at a higher latitude), most of this irradiation is potentially usable for heating purposes as described in Fig. 1 bottom.

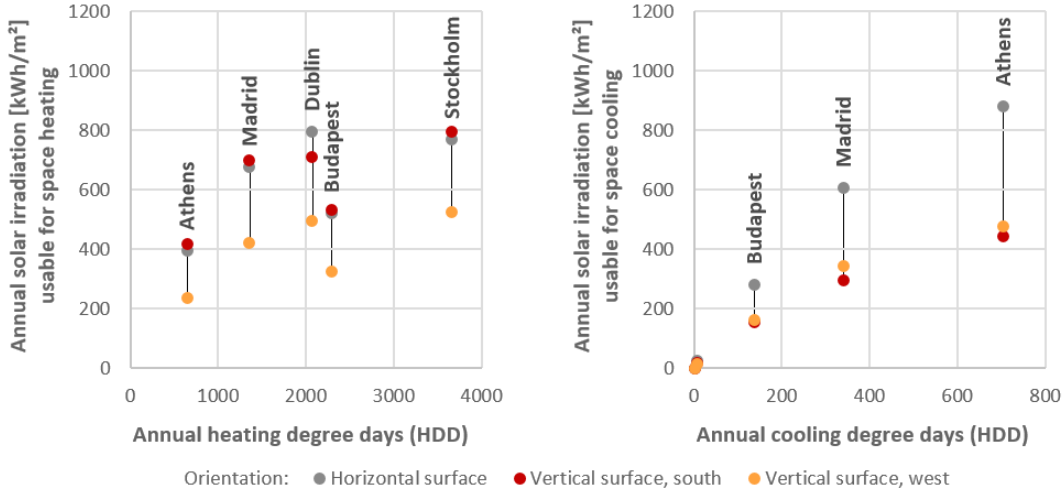

FIG. 12 Relationship between usable annual solar irradiation for heating (left) and cooling (right) in relation to the total demand expressed as annual HDD and CDD, respectively.

LOCATION	ORIENTATION	USABLE FOR HEATING	USABLE FOR COOLING
Madrid	Horizontal	77%	99%
	Vertical south	80%	48%
	Vertical east	48%	56%
Athens	Horizontal	78%	97%
	Vertical south	83%	49%
	Vertical east	47%	53%
Budapest	Horizontal	78%	99%
	Vertical south	79%	55%
	Vertical east	49%	57%
Stockholm	Horizontal	76%	95%
	Vertical south	79%	65%
	Vertical east	53%	59%
Dublin	Horizontal	83%	–
	Vertical south	75%	–
	Vertical east	52%	–

TABLE 1 Percentage of solar energy usable for space heating and cooling, for each city and plane orientation, in comparison with the optimal angle for solar collection.

Fig. 2 and Table 1 assess the usability of solar gains for space heating and cooling, depending on the specific climate and orientation. Taking as a reference the maximum angle where the total solar collection is maximised, there is always a reduction of the collected energy when a horizontal, south, or west/east plane is adopted, aiming to integrate these solutions within the envelope. Looking at the share of expected gains that is exploitable for heating and cooling purposes, some general recommendations can be appreciated and considerations given.

For solar heating production, the southern façade is the most interesting orientation as it provides a regular profile throughout the whole year, smoothing the summer profile and reducing peaks in that season when heating is not requested (top row in Fig. 1). It represents an interesting option for heating, providing 75% - 83% of the energy that would have been collected at the maximum orientation among the cases studied (Table 1). It is worth noting that, in all cities assessed except Dublin, the irradiation usable for heating in a south-facing plane is higher than for a horizontal plane, which is the commonly used source of information in weather databases.

For solar cooling production, the more interesting angles are those that maximise absolute gains, because the most intensive cooling needs are coupled with the period of highest solar production. Even horizontal surfaces can harvest 95% - 99% compared to the orientation of maximum gains (Table 1). However, if roof surfaces are limited or unusable, especially when retrofitting, west and east façades replicate the distribution of solar gains over the duration of the year (top row in Fig. 1), although this results in a significant reduction and meets around 53% - 57% of energy demand for those cases with relevant cooling requirements.

5 EXAMPLES OF INTEGRATED SOLAR TECHNOLOGIES

The results presented above have demonstrated that a significant quantity of solar energy reaches the different planes of buildings. This energy, which can be employed to produce heating and cooling, represents an interesting opportunity to integrate solar technologies within buildings.

	VACUUM PIPE	FLAT PLATE	UNGLAZED
Temperature (°C)	100 – 140	50 – 100	25 – 50
Power (kW/m^2)	1.6 – 2.2	1.5 – 2	1 – 1.2
Average production (kWh/m^{2}a)	480 – 650	400 – 600	300 – 350
Average cost (€/m^2)	800	370	220

TABLE 2 Characteristics of the three main technologies for solar thermal panels.

An overview of currently available solar technologies for thermal collectors is presented in Table 2, based on research for panels installed in Switzerland (Munari Probst & Roecker, 2012). With regard to photovoltaic technologies, the wide range of currently available systems and recent developments have boosted the efficiency of such systems, while the cost is continuously decreasing. In any case, values ranging between 0.15 – 0.3 kW/m^2 for an annual production of 100 - 300 kWh/m^2 and a cost of 1500 - 4000 €/m^2 are representative of such solutions (IRENA, 2012; IRENA, 2017).

When combining the available solar energy with the characteristics of each technology, the potential for integrating these into the envelope can be appreciated. Considering mainly thermal solutions due to their higher efficiency, the possibilities for solar heating are wide and all the technologies can contribute to reducing the demand for non-renewable energy sources. On the other hand, solar cooling requires high temperature levels achievable only by vacuum tube collectors and some flat plate systems. The exploitation of electricity from PV panels is more straightforward for both heating and cooling, reducing the electricity consumption of energy provision devices such as heat pumps.

LOCATION	PRIORITY PRODUCTION	HIGHEST POTENTIAL FOR SOLAR INTEGRATION	
		ORIENTATIONS	TECHNOLOGIES
Stockholm	Heating (100%)	South vertical	Unglazed, flat plate, vacuum, PV
Dublin	Heating (100%)	South vertical	Unglazed, flat plate, vacuum, PV
Budapest	Heating (94%)	South vertical	Unglazed, flat plate, vacuum, PV
Madrid	Heating (80%)	South vertical	Unglazed, flat plate, vacuum, PV
Athens	Cooling (52%)	Max. exposure (30°), west, east	Flat plate, vacuum, PV

TABLE 3 Assessment of the interest for integrating solar technologies as a function of location and of most beneficial orientation for each case.

Discarding the horizontal plane and taking into consideration the predominant demand in each climate, Table 3 assesses the interest for integrating a number of solar technologies in the specific locations and orientations assessed in this study, considered to be representative of many locations within Europe. The choice of systems to integrate is quite varied, except for unglazed panels in locations where cooling is pursued. This limitation is not so important in climates with a predominant demand for heating, where such solutions are very interesting due to their lowest investment required. On the other hand, the consideration of which orientation has the highest interest is critical for an effective integration process and ultimately for achieving a cost-effective payback of the intervention.

As exemplar applications of such solutions, flat plate, unglazed, and PV panels provide a high level of integration for opaque areas, while vacuum pipe panels offer interesting possibilities for glazed areas as well as for opaque zones. The external glass of PV and flat plate technologies also allows certain combinations and interactions with glazed areas, although the collectors will not allow natural light to get inside the building.

Fig. 3 shows flat plate and unglazed panels covering opaque areas, providing good efficiencies for heating in south vertical façades. An application for glazed areas where vacuum pipe panels are integrated is portrayed in Fig. 4. For a case such as the one in Athens, where cooling and heating loads are quite similar, such panels can be employed in a south orientation for heating and in east or west orientation for cooling production. In addition, these solutions are also applicable for heating generation in other locations and in the south façade, although the effect of solar gains will require a detailed assessment to avoid overheating during summer, probably requiring filtered glasses within the solution.

FIG. 1 Left. Glazed flat plate collector integrated into a modular façade system (Winkler Solar, n.d.), Right. Prototype of unglazed collector integrated into a metal cladding panel (Elguezabal, Garay & Martin, 2017).

FIG. 2 Left. Vacuum pipe collectors integrated into a modular curtain wall providing a glazed façade. Right. Detail of the prototype (University of Stuttgart, n.d.)

6 CONCLUSIONS

The potential for the exploitation of solar energy is very significant, since it is a renewable resource available in the environment in high quantities. This challenge supposes that, in addition to conventional measures such as increasing insulation levels and equipment efficiency, it is necessary to seek to integrate renewables in buildings through their envelope, turning them into a key element in the transformation of buildings in relation to energy exploitation. It is very important to consider the coupling of production and consumption to improve system performance and avoid inefficiencies in management and distribution. Endeavouring to meet the NZEB requirements, buildings will increasingly be required to be more and more self-sufficient, while their connection to the main supply networks should decrease until they eventually become negligible. This will imply the introduction of solar collecting devices comprising a significant surface area. The available surface in the optimal orientations varies depending on the demand that is expected to be covered, but limitations are common especially when retrofitting is pursued. In such situations, alternatives to the optimal orientations need to be considered.

The present study has investigated different scenarios regarding the integration of solar collecting devices into the building envelope and their potential to be exploited for space heating and cooling, resulting in some interesting key findings.

It is important to consider the dominant demand for each climate since this has a significant impact on the maximum usable energy. In many cases, the placement of solar collectors in vertical façades instead of on the roof could provide benefits, especially for solar heating, as collection and demand achieve a better coupling on south-facing orientations. To cover space heating demand with solar energy, the south vertical orientation is very promising in all five cities studied. Although some energy is not used, the benefits of getting a regular production profile could represent a general improvement compared to the maximum angle orientation. As an additional reason to consider vertical façades for the incorporation of energy harvesting systems, the available surface of the façades is usually greater than that of the roof, and increases more for slender and block buildings.

If the cooling demand is greater than the heating demand, or in a similar range of magnitude, the advantage of the south orientation is not so obvious, since the east and west cases can maximise cooling production in summer, but their production goes below the south case in winter. For such applications, more detailed studies would be needed, making comparative designs between different orientations and combinations and taking into account the cost and return on investment associated with energy savings.

Finally, some currently available and recently developed thermal and PV solutions have been shown as examples of the applicability for integrating solar technologies. Taking into consideration their performance, efficiencies, and costs, as well as the main interest for placing them in specific envelope orientations, the potential of these solutions has been highlighted, providing general recommendations about the convenience of their integration, aiming to contribute to a higher penetration of RES within buildings.

Future research could build on the findings from these studies, by considering the impact of the efficiency curves for different solar technologies, on the one hand, and the influence of building shape and insulation levels on the energy demand, on the other hand. This would allow a direct comparison of on-site energy production and consumption, as well as their distribution over time and the usage of common metrics (Cao, Hasan, & Sirén, 2013) for assessing the correlation between supply and demand.

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